THE IMPACT OF THE F/A-18 AIRCRAFT DIGITAL FLIGHT CONTROL SYSTEM AND DISPLAYS ON FLIGHT TESTING AND SAFETY

by
B. T. Kneeland, W. G. McNamara, C. L. White
Flight Systems Branch
Strike Aircraft Test Directorate
Naval Air Test Center
Patuxent River, Maryland 20670
USA

SUMMARY

This paper overviews the development of the digital fly-by-wire Flight Control System (FCS) in the F/A-18 aircraft. A general description of the FCS and an overview of the significant changes that have been incorporated to improve handling qualities and to correct anomalies that were discovered during the Full Scale Development (FSD) program are presented. The interface of the FCS with the total avionics package of the F/A-18 via the 1553 multiplex bus and the impact of this interface on specific flight testing and FCS development is also highlighted. The impact of the flight control laws on high Angle of Attack (AOA) handling qualities, including a discussion of the changes that were made as a result of a spin accident in November 1980, is presented. Throughout the discussion, references to the specialized displays and controls that are implemented in the F/A-18 to assist the pilot and enhance flight testing and safety are discussed.

LIST OF SYMBOLS

α	Angle of Attack
ADC	Air Data Computer
Ay	Lateral Acceleration
$C_{N_{\beta Dyn}}$	Directional Divergence Parameter ($= C_{N_\beta} \cos\alpha - \frac{I_z}{I_x} C_{l_\beta} \sin\alpha$)
C_{l_β}	Lateral Stability Derivative
C_{n_β}	Yawing Moment Coefficient
C_m	Pitching Moment Coefficient
dB	Gain in Decibels of Bandpass Filter
ΔQ_{c_1}	Differential Dynamic Pressure
δ_H	Stabilator Deflection
δ_R	Rudder Deflection
Fs/g	Longitudinal Stick Force/g
G	N_y Units
I_x	Roll Inertia
I_y	Pitch Inertia
I_z	Yaw Inertia
K	Gain of Bandpass Filter
L/D	Lift/Drag Ratio
N_y	Lateral Acceleration
N_z	Normal Acceleration
OAT	Outside Air Temperature
P	Roll Rate
P_s	Static Pressure
q	Pitch Rate
q_c	Dynamic Pressure
q_{ci}	Dynamic Pressure, Indicated
R	Yaw Rate
S	Wing Area
TA	Ambient Temperature
TAS	True Airspeed
τ, λ	Time Constant, sec
τ_1	Time Constant in Pade Approximation in Bandpass Filter
τ_2, τ_3	Real Roots in Numerator of Bandpass Filter
$\omega_1, \omega_2, \omega_3$	Frequency of Numerator and Denominator Terms in Bandpass Filter
ξ_1, ξ_2, ξ_3	Damping of Numerator and Denominator Terms in Bandpass Filter

FLIGHT CONTROL SYSTEM DESCRIPTION

The FCS in the F/A-18 employs a full authority, high gain control augmentation mechanization. Early versions of the FCS (3 series and 4 series Programmable Read Only Memory (PROMS)) utilized applied stick forces to generate the electrical inputs required to control the aircraft. A major FCS design philosophy change was implemented in 6.X series and subsequent PROMS so that stick position vice stick force is utilized to generate the electrical inputs which are then routed to the flight control computers (FCC) to be processed through specified control laws to provide desired aircraft response (figure 1).

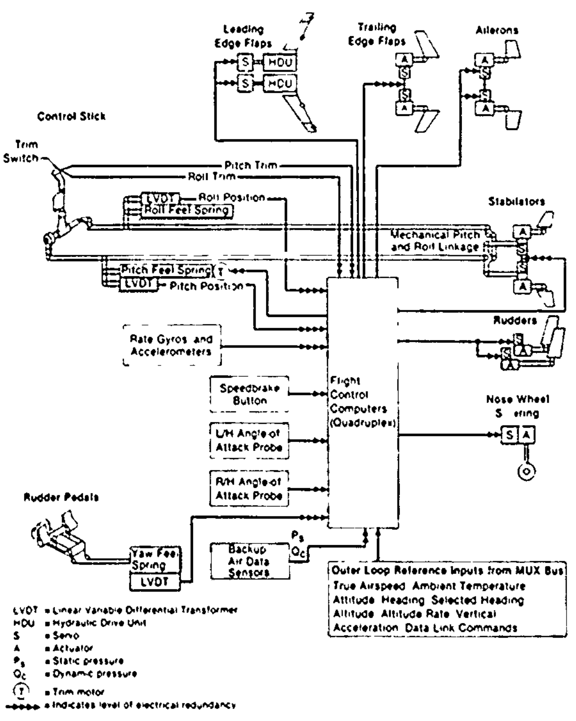


Figure 1 F/A-18 FCS Functional Diagram

Primary pitch control is provided by symmetric deflection of horizontal stabilators. Trailing edge and full span leading edge maneuvering flaps provide optimum lift-to-drag ratios for maneuvering, cruise and high AOA flight conditions. In approach configurations, leading edge flaps and rudders (toed-in) are scheduled with AOA to improve longitudinal stability characteristics. Trailing edge flaps are scheduled with dynamic pressure (q_c) to a maximum deflection of 30 or 45 degrees (TED) dependent on flap switch position. The ailerons are symmetrically drooped to match the scheduled trailing edge flap deflection. A speed brake located on the upper surface of the aft fuselage provides drag control in the cruise configurations (Flaps-UP/AUTO). Roll control is provided by conventional ailerons, differential stabilators, and differential deflection of the leading and trailing edge flaps (differential flap deflections are dependent on flight conditions). Directional control is provided by dual rudders. A rolling surface to rudder interconnect (RSRI) is used to improve turn coordination. Also, a rudder pedal to roll command signal is used to improve roll response at

higher AOA in cruise configuration and to reduce sideslip excursions in approach configurations. The control laws automatically revert to a SPIN mode if specific yaw rate conditions are exceeded to facilitate recovery from out of control flight. Additionally, pilot relief modes are provided through the autopilot to facilitate weapon system management.

Power to the FCS is supplied by 28 Vdc Power from the aircraft's electrical system. Four independent branches of the hydraulic system provide primary and backup hydraulic pressure to the surface actuators. For three similar failures of motion feedback sensors in a given axis, control is accomplished using a digital Direct Electric Link (DEL) mode, which provides a direct electrical path from the pilot input sensor to the control surface actuator. Should three digital processors fail, longitudinal and roll control is accomplished by a backup mechanical mode to the stabilators. The mechanical controls are conventional cable, push rod, and bellcrank systems. In the mechanical backup mode, stick-to-stabilator gearing is modified by a nonlinear linkage to provide the desired sensitivity between stick forces and deflections or all flight conditions. Aileron or rudder control is available in the mechanical mode through an analog DEL path. In the event of a total electrical failure, only mechanical control of the stabilators is available.

Reliability and maintainability of the FCS have been enhanced during the FSD program by continued improvements to the designed Built-in-Test (BIT), the memory inspect (MI), and the maintenance monitor capability. Additionally, expanded maintenance advisory information is available through the incorporation of BIT Logic Inspect (BLIN) capability. This feature provides the capability to automatically search the flight control computer memory to obtain relevant failure isolation data and display it by channel on the cockpit displays. A more complete description of the BIT, MI, and BLIN features is contained in reference 1.

FLIGHT CONTROL SYSTEM INTERFACE

The FCS interfaces with other avionics in the F/A-18 via a 1553 multiplex bus as shown in figure 2. It is this interface capability which, in conjunction with the unique FCS displays and controls, aided the development and testing of the FCS. The mission computer (MC) FCC interface was designed to allow the FCC's to receive data for outer loop control computations and initiated BIT commands and to transmit sensor data, flight test data, and BIT results to the other avionic components in the aircraft. The BLIN and MI inspect features mentioned earlier are also dependent on the interface capability provided by the 1553 multiplex bus. During the course of FCS development, the MC-FCC interface provided a unique capability for specialized diagnostic testing in the areas of performance, high AOA, and development of the active oscillation controller.

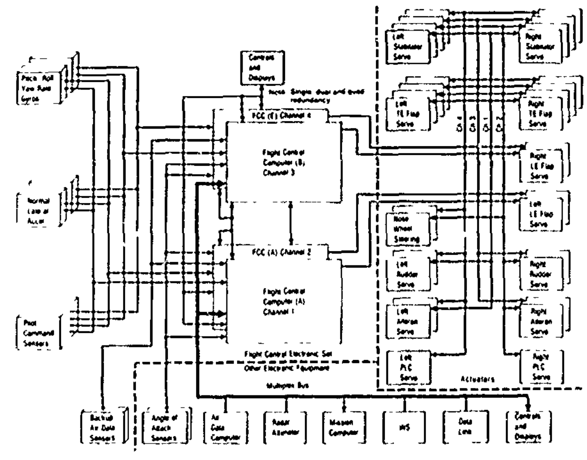


Figure 2 Flight Control Interface

SPECIALIZED CONTROLS AND DISPLAYS

Several specialized displays and controls were incorporated to enhance safety and facilitate FCS testing. FCS controls and displays are shown in figure 3. Special displays that aided in FCS testing included the FCS failure matrix display shown in figure 4 and the specialized SPIN displays discussed later in this paper. The FCS failure matrix display provided the pilot with status information on which FCS shutoff valve or sensor had failed whenever a FCS caution occurred. Additionally, a reset feature was provided via a button on the flight control panel (figure 3). Positive indication of a successful reset for a given failure was provided by removing the X from the FCS failure matrix. This same information was provided via a similar binary display panel in the ground station which displayed FCS status to ground test personnel.

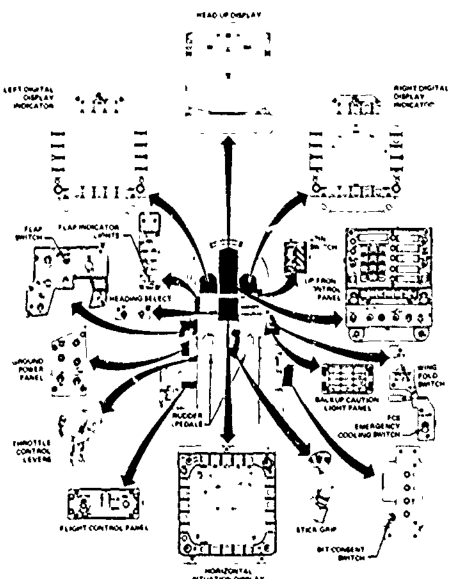


Figure 3 FCS Controls and Displays

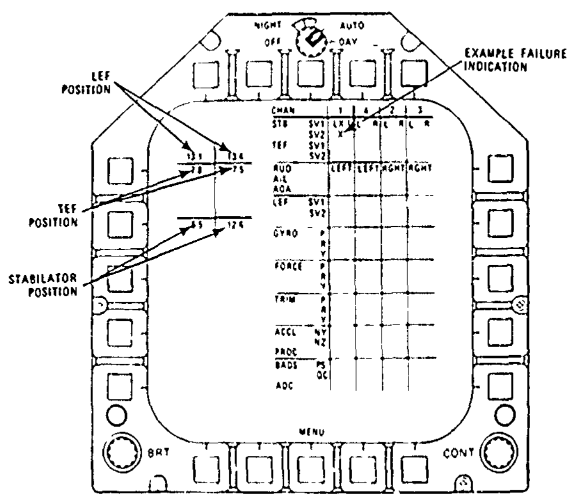


Figure 4 FCS Failure Matrix Display

FLIGHT CONTROL SYSTEM DEVELOPMENT

GENERAL

Throughout the FSD flight test program of the F/A-18 airplane, several updates and changes to the basic control laws that provide the signal shaping between pilot command inputs and resultant control surface commands have been made. The versatility of the digital design of the F/A-18 FCS provides a unique and practical way of implementing any desired control law changes. Control laws are programmed on a number of PROM modules which are mounted on removable boards in each of the two FCC's. Control law changes are introduced by incorporating updated or revised PROM's. Since the first flight in the F/A-18 (18 November 1978), five major PROM series (more than 56 PROM versions) have been evaluated. The major PROM versions tested include 3.X series, 4.X series, 6.X series, 7.X series, and 8.X series PROMS. Table I summarizes the major changes that were incorporated in each of the major PROM series. Control law changes have been incorporated to improve handling qualities at all flight conditions (including high AOA and out-of-control), improve roll performance, reduce structural loads, improve departure resistance characteristics, incorporate and refine pilot relief modes, and provide an active oscillation controller to suppress undesirable in-flight oscillations.

Table I

PROM SERIES VERISON

PROM Version	Reasons for Change	Time Frame
3.X (7 Total) (3.11, 3.12, 3.16, 3.18, 3.19, 3.21, 3.23)	Improve Handling Qualities Improve Carrier Suitability	Nov 1978- Dec 1979
4.X (26 Total) (4.0, 4.1, 4.3.0.X, 4.3.1.X, 4.3.2)	Reduce Time Delays Add RSRI vice SRI Spin Mode Improvements Roll Modifications	Jan 1980- Nov 1981
6.X (4 Total) (6.0, 6.0.1.1, 6.0.1, 6.0.2)	Reduce Time Delays Position vice Force Sensors Autopilot Modes Incorporated	Nov 1981
7.X (14 Total) (7.0, 7.1.X, 7.2, 7.3, 7.4)	Revised Spin Logic Improve Directional Stability AOC Development	Mar 1982
8.X (4 Total) 8.0, 8.1, 8.2, 8.2.1	Throttle Sensitivity Autopilot/APC/ACLS Improvements	July 1982

FCS HIGH AOA CONTROL LAW DEVELOPMENT

Two of the major design goals for the FCS at high AOA were (1) to augment departure/spin resistance and (2) to automatically provide sufficient control authority for recovery from all spin modes. It was also important that FCS air data sensor failures (AOA, Qci, P_S) not degrade high AOA departure/spin resistance or inhibit/prevent recovery from poststall gyrations or spins. During FSD high AOA/spin testing, many changes were made to improve high AOA characteristics and spin recovery capability. On occasion, unexpected FCS response occurred in the high AOA flight region. As a result of these experiences, the FCS has become, at the same time, more complex and more effective in this flight regime. In addition, unique spin recovery cockpit display concepts have been successfully verified that have the potential to significantly increase flight safety. The purpose of this section is to briefly describe some of the design concepts applied in the FCS at high AOA and to relate some of the more significant changes made to the control laws based on test results obtained during FSD flight tests.

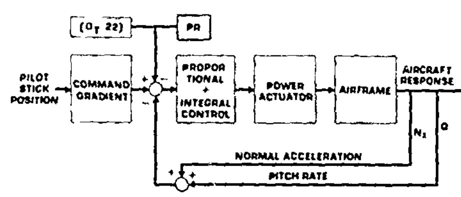


Figure 5 Control Laws - Longitudinal Axis

Longitudinal Axis: A simplified version of current high AOA longitudinal control law mechanization is illustrated in figure 5. Several feedbacks are utilized in the FCS to provide desired high AOA handling qualities characteristics. Normal acceleration feedback provides essentially constant stick force per G at airspeeds above approximately 390 KCAS. Pitch rate feedback is blended with N_z feedback between 390 KCAS and 260 KCAS to improve low airspeed high AOA controllability. Roll rate X yaw rate feedback is utilized to reduce inertia coupling tendencies which were encountered particularly in the 15 to 20 degree AOA region and to reduce vertical tail loads at high airspeed. AOA feedback provides an artificial high AOA stall warning cue by abruptly increasing the stick force per degree g gradient above 22 degrees AOA as illustrated in figure 6. A stall warning tone is generated as AOA increases above 35 degrees. AOA feedback thresholds in order of occurrence have ranged from 23 to 20 to 15 and back to 22 degrees during FSD testing. The design goal was to provide necessary artificial stall warning and at the same time satisfy maneuvering AOA (15 to 30 degrees) handling qualities requirements, particularly in the air combat maneuvering environment (ACM). As an example, the AOA feedback threshold was changed from 15 to 22 degrees due to undesirable Fs/g changes with airspeed. With the threshold set at 15 degrees AOA, it was found that, during simulated ACM evaluations, there was an undesirable change in the stick force per g gradient over a relatively small speed range as illustrated in figure 7. This situation was rectified by shifting the AOA threshold to 22 degrees.

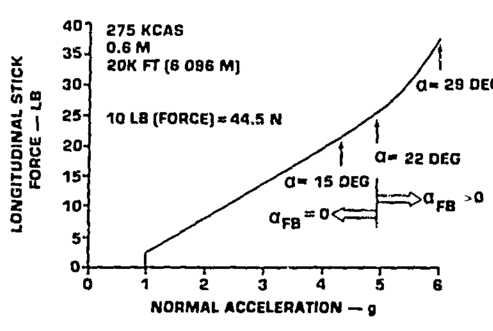


Figure 6 High AOA Feedback Effect on Fs/g

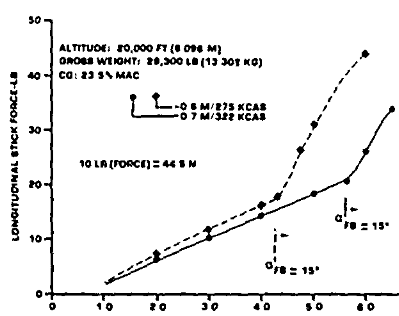


Figure 7 Fs/g Versus Airspeed at 15 Degrees AOA

Maneuvering Flaps: F/A-18 maneuverable LEF and TEF provide increased lift, increased lateral-directional stability, and improved dutch roll damping at high AOA. In the UP/AUTO configuration, LEF and TEF positions are scheduled with AOA and Mach number as illustrated in figure 8. Initial FSD high AOA flight tests focused on lateral-directional stability and control characteristics at AOA's between 15 and 45 degrees. During this testing, maximum LEF deflection was 25 degrees at AOA's above approximately 25 degrees. Results of testing at approximately 35 degrees AOA showed a marked reduction in $C_{N_{\beta_{Dyn}}}$ (Directional Divergence Parameter), as shown in figure 9, due to a significant decrease in lateral stability. The level of $C_{N_{\beta_{Dyn}}}$ at AOA's less than $C_{L_{MAX}}$ was considered unacceptable. As a result, LEF maximum deflection at high AOA was subsequently increased to 34 degrees. As shown in figure 9, the increased LEF deflection provided increased departure resistance. This was obtained as a result of increased lateral stability up to approximately 40 degrees AOA. The trailing edge flap scheduling strongly affects dutch roll damping and L/D ratio. Current F/A-18 control laws command the trailing edge flaps to the full retracted position at maneuvering AOA's approximately 20 degrees.

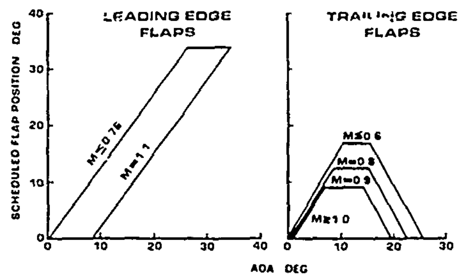


Figure 8 Maneuvering Flap Schedules

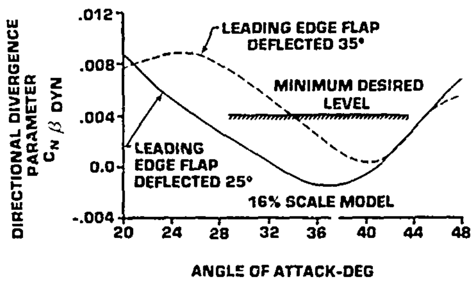


Figure 9 $C_{n_{\beta_{Dyn}}}$ Variation with LEF Position

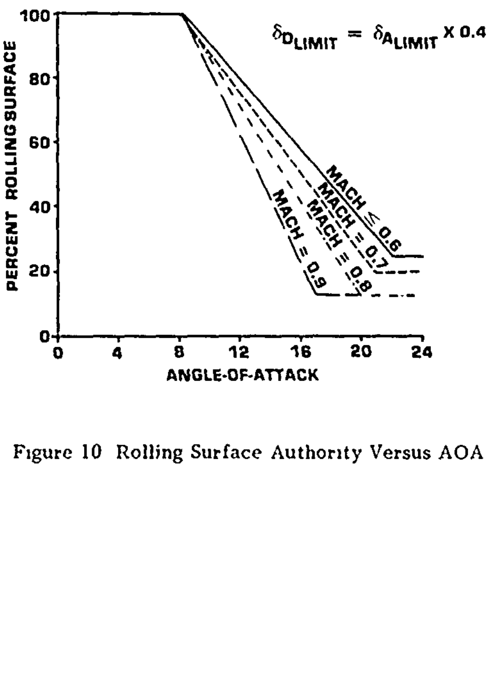


Figure 10 Rolling Surface Authority Versus AOA

Lateral-Directional Axes: Departure and spin resistance is further increased by reducing differential tail and aileron authority at high AOA's (figure 10). The design intent was to significantly reduce the magnitude of adverse yaw with lateral command while still retaining as much coordinated roll response as possible. The F/A-18 FCS incorporates a rolling surface to rudder interconnect (RSRI), functionally similar to an aileron-rudder interconnect (ARI), which provides a proverse yaw contribution during lateral stick inputs, further reducing the adverse yaw tendencies and improving roll coordination (figure 11). A rudder pedal to rolling surface interconnect (figure 12) is also included in the FCS to reduce proverse yaw during rudder rolls. The improved roll coordination minimizes N_z coupling at high AOA due to kinematic coupling (i.e., interchange of AOA and sideslip during uncoordinated rolling maneuvers). Several feedbacks are utilized at high AOA to augment bare airframe lateral-directional stability (see figures 11 and 12): (a) lateral acceleration feedback for increased directional stability, (b) yaw rate feedback for increased directional damping, (c) pα (roll rate x AOA) feedback for improved roll coordination by rolling the airplane about the stability axis (or velocity vector) vice the body axis, (d) roll rate feedback for increased Dutch roll damping, and (e) PQ (roll rate x pitch rate) and PR (roll rate x yaw rate) feedback to reduce inertia coupling tendencies.

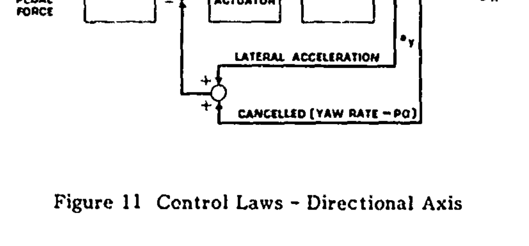


Figure 11 Control Laws - Directional Axis

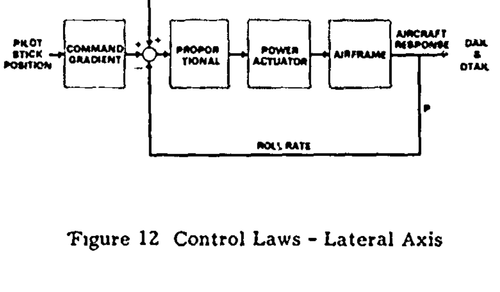


Figure 12 Control Laws - Lateral Axis

FCS Control Law Inertia Coupling Compensation: During FSD high AOA departure resistance testing, negative g departures occurred in the middle of the maneuvering envelope (15 to 20 deg AOA region) when aggravated controls were applied for even brief periods of time (less than 2 seconds). Data analysis indicated that these departures were primarily caused by roll coupling. The combined effect of roll coupling in combination with adverse sideslip led to excessive vertical tail loads and occasionally, to negative g excursions approaching the negative g structural limit. The versatility of the FCS was again demonstrated, in this case, by use of inertia coupling feedback compensation.

An examination of the equations of motion shows that sideslip and g overshoots during rolling pullouts can be reduced if inertial coupling moments can be alleviated. Roll-yaw coupling generates pitch accelerations by roll rate times yaw rate multiplied by an inertia characteristic ratio:

$$q = pr\ (Iz - Ix)/Iy$$

Similarly, roll-pitch coupling causes yaw acceleration by roll rate times pitch rate multiplied by another inertia characteristic ratio:

$$r = pq\ (Ix - Iy)/Iz$$

Therefore, appropriate rudder and elevator deflections were programmed into the flight control PROMS as a function of dynamic pressure and body axis rates to counter yawing and pitching moments due to inertial coupling:

$$\delta_r = pq\ (Iy - Ix)/qsb\ C_{n_{\delta_r}}$$

$$\delta_H = pr\ (Ix - Iz)/qsc\ C_{m_{\delta_H}}$$

Figure 13 illustrates the effect of inertia coupling compensation during a full lateral stick input. The magnitude of AOA unloading is reduced considerably when the inertial-coupling compensation is engaged. Full lateral stick rolls were also markedly improved and vertical tail bending moments were reduced to below design values. This proved to be one of several instances where a FCS software programming change solved difficult flying qualities/structural problems that would usually have required a hardware change.

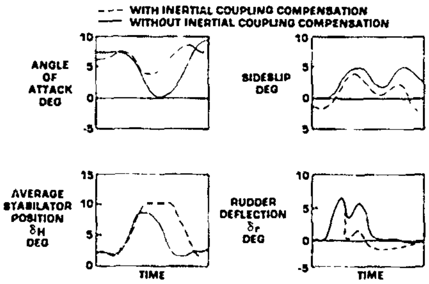


Figure 13 Effect of Inertia Coupling Compensation

FCS Control Law Changes for Improved Departure Resistance: During the later stages of F/A-18 FSD testing, weak directional departure resistance at typical maneuvering AOA was identified. Directional departures occurred at high subsonic Mach number in the 20 to 30 degrees AOA region of the flight envelope, particularly with centerline tank or three external fuel tank loadings. F/A-18 basic airframe plus centerline tank weak directional stability levels at high subsonic Mach number are illustrated in figure 14. Departures at high dynamic pressure flight conditions were of serious concern primarily because of the potential for structural overload of the vertical tails. The result of FCS software changes to correct a significant flying qualities deficiency was again clearly demonstrated. The result of FCS control law changes on departure resistance is illustrated in figure 15. As can be seen, the final control law version (7.1.3 PROMS) was successful in controlling sideslip at high subsonic Mach number which eliminated nose slice departures with symmetric stores loadings.

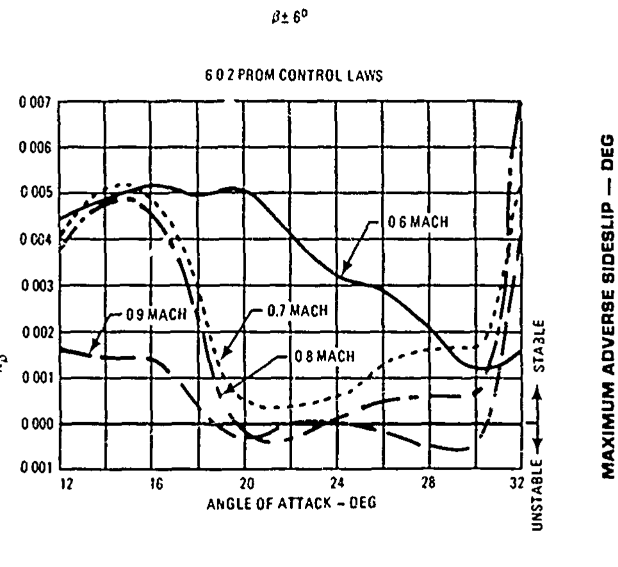


Figure 14 Centerline Tank Loading Mach Number/ AOA Effect on Directional Departure Resistance

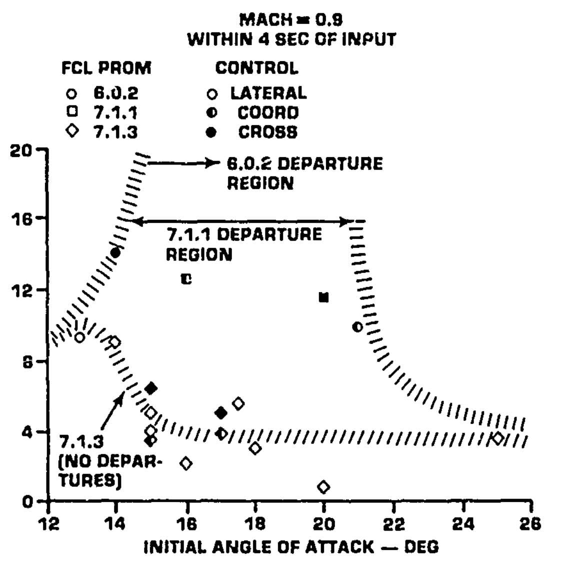


Figure 15 Control Law Effects on Departure Resistance

Evolution of FCS control law changes made to eliminate departures is illustrated in figure 16. The most significant control law changes made were reduced rolling surface authority with increasing AOA and Mach number and significantly increased lateral acceleration feedback to rudder gain. The design tradeoff made was reduced roll rate capability at high AOA/high Mach for increased departure resistance.

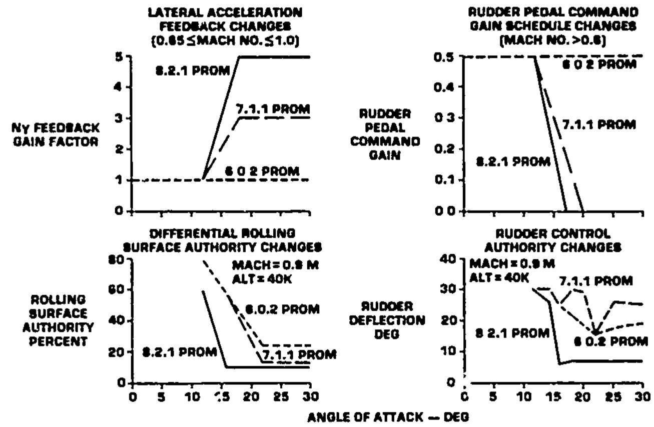


Figure 16 FCS Changes for Improved Departure Resistance at High AOA

FLIGHT CONTROL SYSTEM TESTING

GENERAL

Flight testing of the F/A-18 has involved both the classical stability and control tests (reference 2) listed in table II and specialized frequency sweep techniques (used for equivalent system analysis). Additionally, a major emphasis was placed on the definition and performance of precise mission tasks. A list of the mission tasks evaluated during the development testing of the F/A-18 is presented in table II. The primary evaluation criteria used when evaluating the assigned tasks was the Cooper-Harper Scale reference 3. Handling qualities ratings assigned to these precisely defined tasks have provided the most effective quantifying measurement of the FCS performance during its evaluation. In addition to the handling qualities ratings assigned to mission tasks, the FCS has also been quantified in terms of equivalent system frequencies and damping using a maximum likelihood parameter identification technique reference 4. The use of this parameter identification technique has been very successful in demonstrating the success the contractor has had in reducing the overall system equivalent time delay as the control laws/FCS changes evolved.

Table II

Classical Flight Test Maneuvers

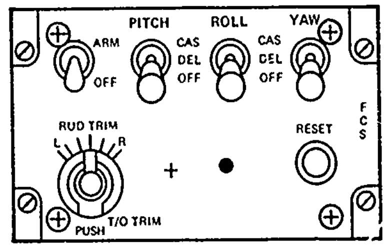
Maneuver
Doublet
Pitch and Bank Attitude Captures
Frequency Sweeps
Wind-Up Turn
Wind Down Turn
Sudden Pull Ups
Full Deflection Rolls

Primary Mission Tasks

Mission Task	Performance Criteria
Column Formation 300 KCAS/2 g 400 KCAS/4 g	Maintain position (20 feet nose-to-tail, 20 feet stepdown) ±10 feet at 400 KCAS/4g; ±5 feet at 300 KCAS/2 g.
Aerial Refueling 250 KCAS	Engage and maintain a plugged position.
Air-to-Air Tracking 300 KCAS/2 g 350 KCAS/3 g 400 KCAS/4 g	Track a stabilized target at specified flight condition. Maintain pipper ±2 mils on targets tailpipe while maintaining 1500 feet nose-to-tail distance.
Air-to-Ground Tracking 30° Dive 45° Dive 60° Dive	Maintain pipper ±2 mils on target.

Special Flight Control Panel: A special flight test flight control panel was provided in selected FSD aircraft to permit flight testing of the degraded modes of the FCS. The design features of this special flight control panel allowed the pilot to select the DEL or mechanical mode of the FCS in each control axis (pitch, roll, or yaw). Figures 17(a) and (b) show the special flight test flight control panel and defines the mode selected with each switch position. Selection of the different available modes required the pilot to select the desired mode, place the arm switch to arm, then depress the nosewheel steering/designate switch on the control stick. Disengagement from the selected mode and reversion to the normal CAS mode was rapidly available by depressing the autopilot disengagement switch on the control stick.

This same special flight test control panel was also utilized during diagnostic testing of the various roll modifications. Use of the special panel to deselect portions of the roll modifications is also shown in figure 17(c). The significant difference between using the panel for degraded modes and as a diagnostic tool to assess the roll modifications was the position of the arm switch. If the arm switch was on, the appropriate degraded mode was selected. If the arm switch was off, then a portion of the roll modification was inhibited.



Flight Test Modes are engaged by:

1. Select desired pitch, roll, or yaw mode
2. Arm the system.
3. Engage with NWS switch.
4. Disengage with autopilot disengagement switch.

Figure 17(a)

The following conditions can be obtained with the mode switches (6.X series):

Switch Position	Pitch	Switch Roll	Yaw
CAS	Pitch CAS to stabilator.	If yaw CAS is selected: Roll CAS to ailerons. Roll CAS to stabilators if stabilators are not in mechanical. If yaw DEL is selected. Rol digital DEL to ail. Roll digital DEL to stabilators if stabilators are not in mechanical.	Yaw CAS to rudder.
DEL	Pitch digital DEL to stabilators.	Digital DEL to ailerons. Roll DEL to stabilators if stabilators are not in mechanical.	Yaw digital DEL to rudders.
OFF	Stabilators to mechanical.	Roll CAS to stabilators if stabilators are not in mechanical. Analog DEL to ailerons and rudders.	Not available switch position blocked.

Figure 17(b)

Ft Panel Switch Position	Arm Switch Position	Feature Selected[1]
PCAS - OFF	OFF	Reduces total differential stabilator to ± 20 deg.
PDEL	OFF	Disengage differential LEF.
RCAS - OFF	OFF	No reversed aileron gain or aileron disengaged.
YCAS - OFF	OFF	Differential TEF disengaged.

NOTE: (1) Features can be selected individually or all combination.

Figure 17(c)

"Fixed Flap" Mode: The "fixed flap" mode was originally intended to provide a means to optimize the maneuvering flap schedules for cruise performance. The cabability was also used to develop flap schedules to improve approach airspeeds and to improve departure resistance and spin recovery during the high AOA test program. A modified version of the "fixed flap" mode was used to develop the active oscillation controller. The basic design and operation of the "fixed flap" mode demonstrates the flexibility and versatility of the FCC-MC interface in the F/A-18. The MC was programmed to accept a 4 X 2 matrix of data information. In the case of the performance and high AOA testing, this 4 X 2 matrix consisted of four pairs of leading and trailing edge flap commands. In the case of the active controller development, these fixed pairs of data corresponded to gain and phase shifts to a nominal bandpass filter. Operation of the fixed flap mode is summarized in figure 18(a). Changes to the programmed settings could also be made by the pilot or ground personnel via the Up Front Control as described in figure 18(b).

OPERATION OF "FIXED FLAP MODE"

1. Arm the "fixed flap" mode via UFC.
2. Select A, B, C, or D setting on FCES display (hold button until "ARM" cue is displayed).
3. Select fixed flap via nosewheel steering/designate button (look for 1234 on display).
4. Deselect via autopilot disengage switch.

NOTE: Four data pairs (A, B, C, and D) can be changed by pilot via UFC in flight or on ground.

Figure 18(a)

CHANGING FIXED FLAP DATA IN MISSION COMPUTER

1. Arm Fixed Flap Mode
Menu BIT MI Unit 28
Address 31214
Data Option
Address 27650 Enter 1
2. Address Appropriate 6 Digit Code for A, B, C, or D setting.
3. Enter 6 Digit Octal Code for Desired Flap Setting.

Figure 18(b)

These changes could be implemented on the ground or in flight. The mode could be quickly disengaged by depressing the autopilot disengage switch (paddle switch) on the control stick. Safety was also enhanced by requiring the fixed flap mode to be activated by a discrete input and by providing positive feedback to the pilot via the special FCS display (figure 18(c)).

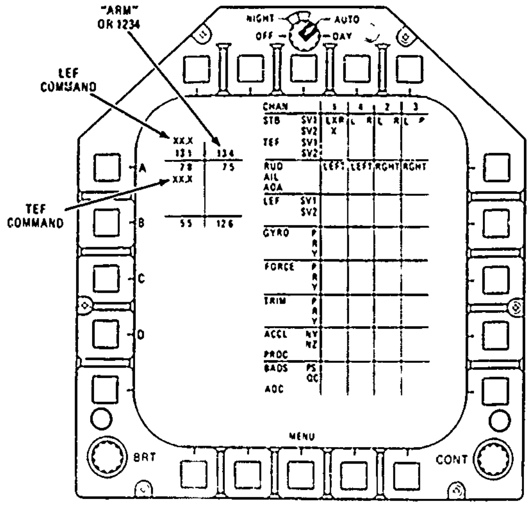


Figure 18(c)

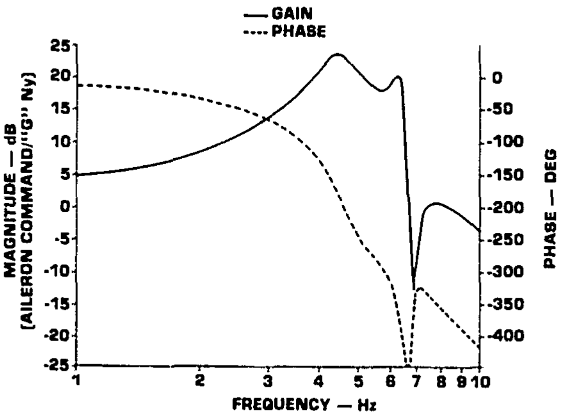
TESTING THE ROLL MODIFICATIONS

One of the two areas of interest during the flight test program that particularly demonstrated the utility of the special flight test control panel was the testing of the roll modifications. As a result of roll performance testing conducted in the F/A-18 with 3 series and 4.1.X series PROMS, several modifications and control law changes were incorporated to improve roll performance in the low altitude transonic flight regime. Initial roll modifications included increasing the wing stiffness, extending the ailerons to the wingtip, incorporating differential trailing edge flap capability ($\pm$8 degrees), increasing differential stabilator deflection from 20 to 26 degrees, and reversing aileron deflection at high dynamic pressure flight conditions. Use of the special flight test panel described previously allowed diagnostic testing to determine the effect on roll performance of the differential trailing edge flaps, the increased differential stabilator authority, and the reversal of aileron commands at high dynamic pressure flight conditions. Results of this initial diagnostic testing provided the data that led to the decision to delete the aileron reversal and decrease the differential stabilator authority in subsequent PROM versions. Subsequent to the initial roll modification testing, further improvements in roll performance in the high transonic, low altitude flight regime were still required. Further testing involved investigating the use of differential leading edge flaps to enhance roll performance in the area of interest. The decision to pursue this course of action was prompted by analysis which indicated that the reduced roll performance at high transonic, low altitude flight conditions was attributable to wing twisting at these high q_c flight conditions. Differential deflection of the leading edge flaps reduced the adverse wing twist and resulted in improved roll performance. Initial testing involved performing 360 degree rolls with the outboard leading edge flaps prerigged to a 6 degree differential deflection. These test results proved favorable and a prototype system was designed and implemented in an FSD aircraft. Testing was accomplished on the prototype system with 4.3.2 PROMS. Diagnostic testing of the effect of the differential leading edge flaps was also possible through the special flight test control panel (figure 17(c)). Results of the diagnostic testing of the various roll modification evolved into the final production roll improvement package which consisted of increased wing stiffness, extended ailerons, and differential trailing and leading edge flaps. Provisions for the production roll improvements were incorporated in the 6.X and subsequent PROM versions.

DEVELOPING THE ACTIVE OSCILLATION CONTROLLER

The area of flight testing that particularly demonstrated the unique flexibility provided by the "fixed flap" capability was the development of the active oscillation controller. During the flutter test program with external stores, objectionable low amplitude directional oscillations (5.6 Hz) were observed at high speed/low altitude flight conditions when heavy stores (MK 80 series bombs) were carried on the outboard weapon stations (stations 2 and 8) with AIM-9's on the wingtip stations. This phenomena was attributed to an asymmetric store pitch mode that coupled with a lateral fuselage bending mode to produce the resultant airplane directional response and lateral acceleration oscillations perceived by the pilot. Analysis of the phenomena indicated that the oscillations were affected by the presence of AIM-9's on the wing tip weapon stations (stations 1 and 9), leading edge and trailing edge flap deflections, and aileron deflections. Based on these observations, early fixes concentrated on scheduling the leading edge flaps and ailerons to effectively eliminate or reduce the magnitude of the oscillations. This approach resulted in schedules that positioned the leading edge flaps 3 degrees leading edge up and the ailerons 4 degrees trailing edge up. These schedules were implemented in the 6.0.2 PROMS and successfully reduced, but did not eliminate, the occurrences of the 5.6 Hz oscillations. The resultant LEF flap schedule also created problems with in-flight loads and leading edge flap operation. Subsequently, a decision to explore an active oscillation control (AOC) mechanization was made. The AOC concept involved using signals from existing FCS sensors to drive the control surfaces to damp out the objectionable 5.6 Hz oscillations. Initial flight test developement involved utilizing a modified flutter exciter control unit (FECU). This FECU was used during the flutter test program to develop an analog filter to suppress the undesired oscillations. Provisions for pilot selectable phase and gain, selectable forward or aft sensor package input, selectable sensor input (lateral accelerometer, yaw rate gyro, or roll rate gyro), and selectable control surface (rudder or aileron) were implemented to suppress the oscillations. Results of this testing confirmed the feasibility of using an active controller to suppress the oscillations. Subsequently, an analog system was developed that used the forward sensor package lateral accelerometer signal to drive the ailerons at an appropriate gain and phase to effectively suppress the 5.6 Hz oscillations.

The basic analog system developed was then implemented in a digital form into a set of flight control law PROMS (7.1.3.1). The general form of the filter implemented into the production PROMS including a corresponding bode plot is presented in figure 19. A pilot selectable Dial-a-Gain and Dial-a-Phase capability was also implemented via the "fixed flap" mode discussed earlier. The Dial-a-Gain and Dial-a-Phase capability provided a means to fine tune the gain and phase of the filter implemented in the control laws. The first change resulting from testing the initial digital design was to change from a 7th order to a 5th order bandpass filter to provide less phase variation across the frequency range of interest (5 to 6 Hz). Additional refinements were required to optimize the filter for a range of external loadings. A decision to activate the system only for MK 80 series bombs on the outboard stations was made since test results with lighter external stores showed that the active controller tended to amplify instead of attenuate the oscillations. This required interfacing the controller with the stores management set via the MC and 1553 multiplex bus. The final filter implemented represents a compromise for the MK 80 series bombs external loadings tested that still provided adequate suppression of the 5.6 Hz oscillations.



$$K\frac{\left(\frac{-s}{T_1}+1\right)}{\left(\frac{s}{T_1}+1\right)}\left(\frac{\left(\frac{s}{\omega_1}\right)^2+\left(\frac{2\xi_1}{\omega_1}\right)s+1}{\left(\frac{s}{\omega_2}\right)^2+\left(\frac{2\xi_2}{\omega_2}\right)s+1}\right)\left(\frac{\left(\frac{s}{T_2}+1\right)\left(\frac{s}{T_3}+1\right)}{\left(\frac{s}{\omega_3}\right)^2+\left(\frac{2\xi_3}{\omega_3}\right)s+1}\right)$$

NOTE: FINE TUNING THE FILTER INVOLVED CHANGING THE K AND T_1 VALUES VIA THE "DIAL-A-GAIN" CAPABILITY

Figure 19 General Form of the Production Bandpass Filter

FCS SPIN RECOVERY MODE DESIGN EVOLUTION

INITIAL CONCEPTS

During the initial design stages of the F/A-18, a great deal of emphasis was placed upon achieving a design that would possess a high degree of departure and spin resistance. The YF-17 which was the prototype for the F/A-18 was known to possess excellent high AOA flying qualities and, as such, the basic aerodynamic design was chosen as a basis for that of the F/A-18. A comparison of the original and current F/A-18 aerodynamic configuration is illustrated in figure 20. The normal operating mode of the FCS is the Control Augmentation System Mode (CAS). The CAS Mode augments the natural aerodynamic stability via control surface authority limiting and use of feedback control concepts

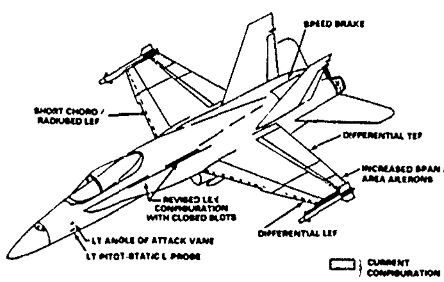


Figure 20 F/A-18 Aerodynamic Configuration

Although lateral-directional control law features in the CAS mode enhance departure/spin resistance, they also reduce control power available for spin recovery. For this reason, an automatic spin recovery mode (ASRM) was incorporated in the FCS. When engaged, the ASRM provides the pilot with full control surface authority regardless of the AOA and opens all feedback loops to provide full antispin control authority for spin recovery.

Automatic Spin Recovery Mode - Initial Design: Establishing safe automatic spin recovery mode (ASRM) engagement/disengagement thresholds was a major consideration before commencement of actual flight tests. The design goal with respect to ASRM logic was to establish engagement thresholds which were not so low as to reduce departure/spin resistance but not so high as to prevent recovery from a spin. Disengagement logic was designed such that the FCS would revert to CAS (i.e., the normal operation FCS mode) during the final stages of spin recovery. While in the ASRM, all feedbacks and control surface limits are removed to provide maximum antispin control authority. It is important to note that pilot spin recovery control inputs are still required in the ASRM. The ASRM does not automatically apply antispin control inputs. During the F/A-18 high AOA/spin FSD program, ASRM logic required changes as more knowledge was gained on F/A-18 spin modes. Initial ASRM engagement/disengagement logic was as shown in figure 21.

- **ENGAGEMENT — YAW RATE $\geq$ 35 DEG/SEC; TIME $\geq$ 5 SEC**
- **DISENGAGEMENT — YAW RATE $\leq$ 15 DEG/SEC**

Figure 21 Original ASRM Logic

During the early stages of the high AOA program, the primary focus of testing was evaluation and/or verification of strong departure and spin resistance. Concurrent National Aeronautics and Space Administration (NASA) F/A-18 drop model spin test results established a requirement to increase the ASRM engagement/disengagement yaw rate thresholds. The basis for this change was a MIL-F-8785B specification requirement that departure resistance be determined by holding sustained prospin control inputs for at least 15 seconds. NASA model testing showed that with ASRM 35/15 degree/second yaw rate engage/disengage thresholds a potential for inadvertent ASRM engagement existed when sustained prospin controls were held for 15 seconds. As a result, ASRM engage/disengage thresholds were increased as shown in figure 22.

- **ENGAGEMENT — YAW RATE ≥ 50 DEG/SEC; TIME ≥ 5 SEC**
- **DISENGAGEMENT — YAW RATE ≤ 30 DEG/SEC**

Figure 22 Revised ASRM Logic

F/A-18 SPIN ACCIDENT

On 14 November 1980, an F/A-18 crashed as a result of a departure that progressed into a low yaw rate spin, which apparently had yaw rates with magnitudes which were less than required to engage the ASRM (50 degrees/second yaw rate). The FCS remained in the Control Augmentation System (CAS) mode. Consequently, insufficient control authority was available for the pilot to achieve recovery. To prevent reoccurrence of these conditions, a cockpit mounted spin recovery mode switch was installed which permitted manual engagement of the spin recovery mode. The manual spin recovery mode (MSRM) switch was installed as an interim fix until such time that the safety and effectiveness of new automatic spin recovery mode logic could be verified. The MSRM switch was also installed in the spin test airplane to permit intentional spin testing for determination of optimum spin recovery control procedures.

Spin Accident Ramifications: The loss of an F/A-18 in an apparent low yaw rate spin had a dramatic impact on the subsequent course of the high AOA test program. Prior to the accident, the major emphasis of testing, as previously noted, was on evaluation of departure and spin resistance. Postaccident testing was expanded to identify all spin modes and to determine optimum spin recovery techniques. In retrospect, it is clear that because of the F/A-18 spin accident and subsequent FSD spin testing, significantly more is known about F/A-18 spin modes, spin recovery characteristics, and operation of the FCS at high AOA than would be otherwise. In particular, as a result of intentional spin testing, the low yaw rate spin mode was identified which is believed to have been responsible for the spin accident. In this regard, initial analytical high AOA simulations and spin tunnel model testing did not predict the existence of this mode as illustrated in figure 23. An example of an actual low yaw rate spin is presented in figure 24.

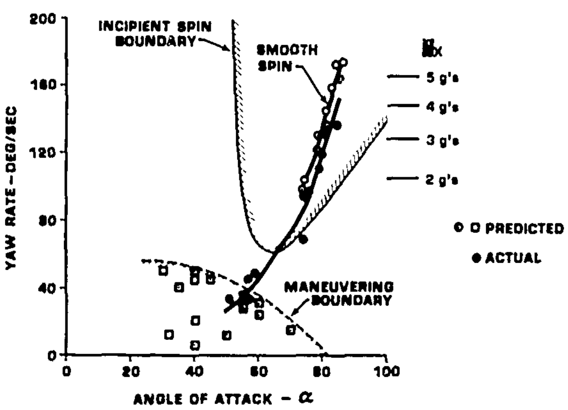


Figure 23 Predicted Maneuver/Spin Boundaries Versus Flight Test

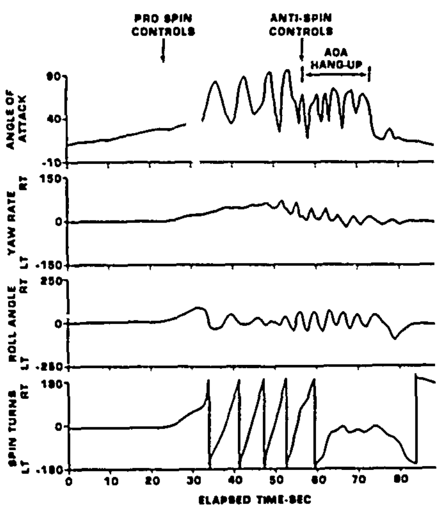


Figure 24 Low Yaw Rate Spin

A contributing factor for no prediction of the low yaw rate spin mode may have been uncertainty in the high AOA aerodynamic data base (rotary derivative data were not available) used to generate the F/A-18 high AOA simulation. Although one of the high AOA piloted simulations (based upon 16% model data) predicted a low yaw rate spin mode approximately 1 year prior to the accident, there was not enough confidence in the data base to lower the automatic spin recovery mode engagement yaw rate threshold. This reluctance may have been due to the excellent departure and spin resistance exhibited by the F/A-18 up to that point in time and because of uncertainty in the aerodynamic data base.

FINAL CONCEPTS

FCS Spin Recovery Mode: As discussed earlier, the F/A-18 FCS was to have only an automatic reversion to spin recovery mode capability. However, as previously noted a cockpit mounted manual spin recovery mode switch was incorporated as a result of the spin accident in November 1980. Evolution of spin recovery mode logic for both the manual and automatic SRM is summarized next.

Manual SRM Logic: Manual SRM engagement/disengagement threshold/logic is summarized in figure 25.

- **ENGAGE LOGIC — SWITCH ON AND <120 KIAS**
- **DISENGAGE LOGIC — SWITCH OFF OR >250 KIAS**

Figure 25 Manual SRM Logic

During the design of the manual SRM, there was a great deal of effort made to insure that the air data system failures previously experienced during FSD flying qualities tests due to sideslip at high airspeed not occur during spin testing. This was necessary because reversion to the fixed gains mode of the FCS would prevent manual engagement of the SRM. This air data failure logic was selected because engagement of spin logic at high dynamic pressure would result in unacceptably sensitive and possibly dangerous aircraft response to pilot control inputs. One of the initial assumptions made was that, during a spin, the total dynamic pressure would be so low that dynamic pressure differences between left and right pitot-static probes could not exceed the preset failure monitor thresholds. However, during asymmetric load spin testing this assumption proved to be incorrect. During a 12,000 ft-lb asymmetric load spin, the difference in left and right Q_{c_i} exceeded the preset failure (ΔQ_{c_i}) thresholds, thereby causing reversion to fixed gains and preventing spin recovery until the failure cleared and the FCS was manually reset. Subsequent analysis revealed that, during the spin, the magnitude of sideslip was such that one of the L-probe pitot-static heads was registering negative dynamic pressure. As a result, the large ΔQ_{c_i} indication caused an air data failure and prevented access to the manual SRM. The air data system failure monitoring logic was subsequently changed so that only positive Q_{c_i} pressure indications are used to compute ΔQ_{c_i} mismatch values, and reasonable range thresholds were expanded to allow negative values. Also, both left and right Q_{c_i} values must fail reasonable range checks before a failure is declared. Excessive differences between left and right dynamic pressure signals will generate a pilot caution but are no longer used to declare an air data failure. During asymmetric load spin testing, reversion to fixed gains also occurred because of larger than expected values of left and right L-probe static pressures due to large sideslip. Left and right static pressure lines are now joined to eliminate that failure mode.

Auto-SRM Logic: As described earlier, the original SRM logic automatically reverted to the SRM if yaw rate exceeded 35 degree/second for ≥ 5 seconds. Automatic reversion to the CAS mode occurred if yaw rate decreased to less than 15 degree/second. As previously noted, engage/disengage yaw rate thresholds were subsequently changed to 50 and 30 degree/second, respectively, to increase departure/spin resistance and to preclude inadvertent SRM engagement during aggressive maneuvering. The need to further modify automatic SRM logic was recognized because of the low yaw rate spin mode identified during spin tests subsequent to the November 1980 spin accident. The ultimate goal was to replace the manual spin recovery mode switch with automatic SRM logic. Current automatic SRM logic is outlined in figure 26. This system has been extensively tested and has provided excellent spin recovery capability. However, additional testing is required to perfect the system to the point at which the manual SRM switch can be removed. A unique feature of current automatic SRM logic is that it provides full antispin control authority only if lateral stick is moved in the correct direction. The FCS automatically reverts/fades back to the CAS mode if prospin lateral stick is applied.

- **ENGAGE LOGIC — AIRSPEED <120 KIAS AND FILTERED YAW RATE X YAW RATE ≥225 (λ=7.2 SEC) AND CORRECT ANTI-SPIN LATERAL STICK APPLIED**
- **DISENGAGE LOGIC — AIRSPEED >250 KIAS OR FILTERED YAW RATE X YAW RATE <225 (λ=3.2 SEC) OR YAW RATE = 0 OR INCORRECT PRO-SPIN LATERAL STICK APPLIED**

Figure 26 Current Automatic SRM Logic

AUTOMATIC SPIN RECOVERY MODE LOGIC/DISPLAY

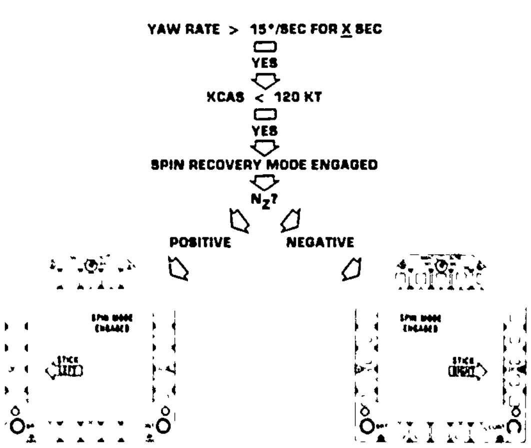


Figure 27 Spin Recovery Mode Display

Spin Recovery Displays: Both manual and automatic SRM logic also provide the pilot with spin recovery mode status information on the cockpit digital display indicators (see figure 27). These displays are specifically designed to provide the pilot with the information he needs to achieve spin recovery. Display information is programmed to appear on both of the cockpit Digital Display Indicators (DDI's). The DDI's are located on the right and left upper portions of the instrument panel. Normally, the DDI's are used to display weapon system information (radar, FLIR, Store Management, etc). However, in an out of control situation, the spin recovery displays have maximum priority and are automatically substituted in place of other display information which may be present. The spin recovery displays are designed to provide the pilot with two essential pieces of information: (a) SRM engage/disengage status and (b) antispin flight control instructions. These displays have tremendous potential for the F/A-18 and for future aircraft designs in that they allow the pilot to make an optimum spin recovery without having to determine the type or direction of spin or to recall the correct antispin controls. One significant problem associated with SRM display information that has been identified occurs during highly oscillatory spins. During intermediate yaw rate oscillatory spins, the F/A-18 will on occasion roll 360 degrees while continuing to spin in the established direction. During the roll, normal acceleration and body axis yaw rate change sign and the spin recovery display arrows momentarily change direction and point in the wrong direction. Review of test data indicates that momentary (i.e., less than 1 second) incorrect spin recovery arrow direction occurs when the sign of raw yaw rate or raw normal acceleration is opposite to that of their respective filtered values (filtered values are used in SRM logic). However, it is important to emphasize that the automatic SRM has operated satisfactorily during spin tests of the F/A-18 and, as such, serious consideration should be given to employing this concept in future advanced tactical aircraft.

HIGH AOA/AIR DATA SYSTEM FAILURE MONITORING

AOA System: The F/A-18 has AOA probes located symmetrically on each side of the forward fuselage as illustrated in figure 20. AOA information is utilized by both flight control and mission computers as illustrated in figure 28.

The FCS converts the two signals from each probe (total of four electrical signals) to digital quantities and through a voting logic computes the AOA signal to be used for control law computations. A correction factor is applied to the local AOA signal to give an approximation to true AOA to be used in control law computations. The range of the AOA probes is -14 to +56 degrees indicated AOA. Above 37 degrees true AOA, the INS is used to compute AOA's up to 90 degrees. This information is displayed to the pilot on the HUD.

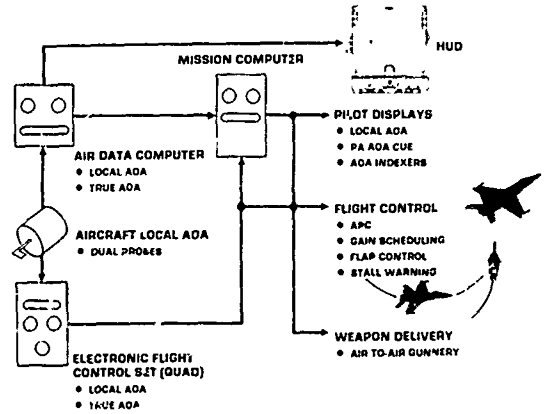


Figure 28 AOA System Configuration

AOA Failure Monitoring: AOA failure monitoring logic changed considerably during FSD testing. Evolution of AOA failure detection logic is briefly summarized in table III. Mismatch tolerances between left and right AOA probes progressively increased to prevent nuisance reversions of the FCS to the "fixed gains" mode. In the fixed gains, LEF's and TEF's are locked in position at time of failure while the FCS remains in the CAS mode. One of the first surprises of the FSD high alpha program occurred during departure resistance testing. During a departure at high subsonic Mach number, unexpectedly large mismatches in left and right AOA vane indications were of sufficient magnitude and duration to cause reversion of the FCS to fixed gains. Upon reverting to fixed gains, the leading edge flaps which should have locked in position at the time of failure, instead retracted, with the airplane in an unrecoverable poststall gyration. Recovery was delayed until the AOA failure cleared and the pilot manually reset the FCS to CAS. Revised control laws subsequently increased the AOA failure detection magnitude and duration thresholds and changed LEF control mechanization to prevent LEF'S/TEF'S from being driven to unusual/off schedule positions. An auto-reset FCS capability was also incorporated in the FCS together with inhibiting of AOA failure monitoring at low airspeed.

Table III

AOA Failure Monitoring Evolution

Tolerance/Threshold AOA Mismatch (deg)	Time Constant	Remarks(1)	Control Law Version
3.5	0.5	Original tolerance/threshold.	3.11
5.0	1.0	Precludes FCS reversions to fixed gains due to sideslip.	3.12
15.0	1.0	Precludes FCS reversions to fixed gains due to sideslip.	3.21
15.0 30.0	10.0 10.0	AOA 15 deg AOA 45 deg	4.3
15.0	5.0	Auto-reset of failure if AOA in reasonable range. AOA failure monitoring inhibited at less than 100 kt.	6.X-8.X

NOTE: (1) In "fixed gains" the FCS remains in the CAS mode with nominal gains used by the flight control laws.

Air Data System: The FCS contains two dedicated dual channel pneumatic pressure sensors called Backup Air Data Sensor Assemblies (BADSA's). The filtered, uncalibrated sensor outputs are used for all inner loop control law gain scheduling. Pneumatic inputs are supplied to the BADSA's and other aircraft systems by two L-shaped pitot-static probes that are located symmetrically on the lower forward fuselage. Each L-probe has two static and one pitot pressure output. Each channel of the BADSA contains an absolute pressure transducer which measures static pressure and a differential pressure transducer which measures dynamic pressure (pitot pressure-static pressure). The air data system configuration is illustrated in figure 29.

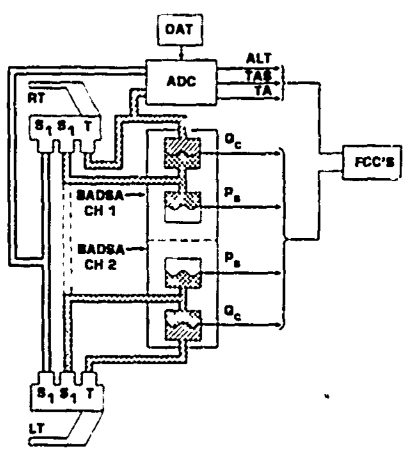


Figure 29 Air Data System

Air Data Failure Monitoring: With current control laws, an air data failure is declared only if both BADSA's fail reasonable range checks. If both BADSA's are in range, then the data from the BADSA with the highest dynamic pressure is used by the control laws. When an air data failure occurs, the FCS reverts to the fixed gains mode. During contractor FSD asymmetric stores high AOA spin testing, reversions to fixed gains occurred as a result of unexpectedly large sustained sideslip excursions which caused excessive differences between left and right static and dynamic pressure signals. These results had a significant impact on spin recovery capability as discussed in a previous section of this paper (see Manual SRM Logic).

HIGH AOA FCS DESIGN LIMITATIONS

One design area in which F/A-18 FCS design limitations become evident occurs at high AOA where nosedown pitch restoring moment requirements must be met. In March 1980, the wing leading edge extension (LEX) slots were closed to improve supersonic performance capability. However, closure of the LEX slots had a significant adverse affect on pitch restoring moment capability at approximately 50 degrees AOA. The zero pitch restoring moment CG was shifted approximately 5% forward (equivalent to approximately 0.1 ΔC_M) as illustrated by figure 30. This has caused delayed recoveries from high AOA flight conditions or AOA hang-up as illustrated in figure 24. Also noted in figure 30 are apparent scale effect differences on pitch restoring moment wind tunnel predictions between 6 and 16% models. Full scale development testing indicated that delayed recoveries from nose high - low airspeed flight conditions and from oscillatory spins were being occasionally encountered. At aft CG's and in the 50 to 60 degree AOA region, the airplane did not always respond immediately to neutral longitudinal controls or application of full forward stick. Subsequent flight testing was performed to identify the CG's at which these conditions (i.e., AOA hang-up) occurred for several external store loadings. The effect of aft CG's in the F/A-18 on AOA hang-up recovery is illustrated in figure 31, which shows that under these conditions full trailing edge down stabilator may not be sufficient to recover from a high AOA condition. As expected, the addition of external wing stores further reduced recovery capability by shifting the zero pitch restoring moment CG as much as 4% forward as compared with the fighter escort loading (wing tip and fuselage missiles only). Interim solutions toward avoiding AOA hang-up flight conditions include modified fuel sequencing to shift the CG forward (approximately 2%) and imposition of AOA/Mach number and CG placards to keep the airplane from entering the AOA hang-up region and to assure adequate recovery control power should AOA hang-up flight conditions be inadvertently encountered. A promising aerodynamic modification that has been designed by McDonnell Douglas and evaluated by NASA Langley Research Center involves a reduction in area of the wing leading edge extension as illustrated in figure 32. Wind tunnel test results (16% scale model) indicate that, in the AOA hang-up region, a 5% aft shift in CG position for zero pitch restoring moment would be realized with the modified LEX as illustrated in figure 32.

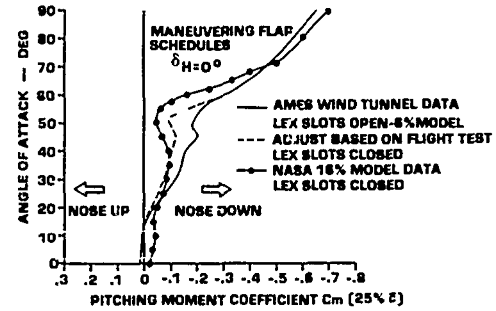


Figure 30 High AOA LEX Slot Effects

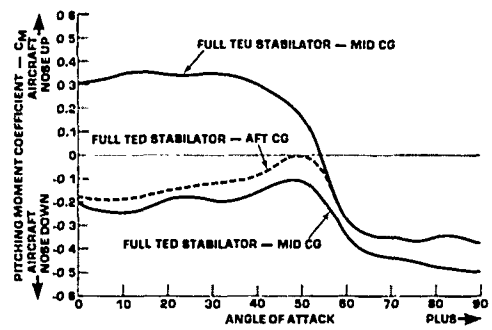


Figure 31 Aft CG AOA Hang-Up Recovery Effect

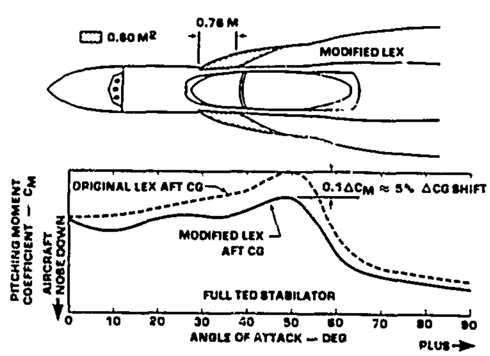


Figure 32 Proposed LEX Modification

FCS design changes can have significant limitations with regard to correcting flying qualities deficiencies particularly at high AOA. In some cases a relatively small aerodynamic design change may be a better and possibly the only solution to a flying qualities deficiency as opposed to a FCS design change for the same purpose.

CONCLUSION

The development of the F/A-18 control laws and specialized displays has been a major stepping stone in demonstrating the powerful flexibility and versatility of a digital FCS as an integral part of a total avionics system. The digital design and interface of the FCS with the MC and pilot displays has been instrumental in improving F/A-18 overall handling qualities, suppressing undesirable structural oscillations, developing high AOA departure resistance and spin recovery control laws, and in developing the associated unique pilot displays which have significantly reduced pilot workload and assisted in spin recovery. The flexibility and versatility inherent in the F/A-18 FCS design has permitted the implementation of unique methods to practicably effect required changes and to refine and develop these changes in a real-time flight test environment. The digital design and integration of the FCS into the overall avionics package of a given aircraft has and will be continually expanded in present and future generation aircraft. Testing of these new systems can be greatly assisted by utilizing their inherent flexibility throughout the flight test program

ACKNOWLEDGEMENTS

Portions of the information and data presented in this paper were obtained from McDonnell Douglas engineering personnel. In particular, special thanks to Messrs. E. H. Anderson, R. Anderson, H. Harschburger, L. Trame, and R. Pelican.

REFERENCES

1. MDC Report A4379, F-18 Flight Control System Schematic Arrangment Drawings, CDRL A03P, Revision F, of 23 December 1982.

2. Langdon, S. D., Fixed Wing Stability and Control Theory and Flight Test Techniques, USNTPS-FTM No. 103, of 1 January 1975.

3. NASA Technical Note TNA 5153 of April 1969.

4. Burton, R. A. and Kneeland, B. T., "F/A-18 High Authority/High Gain Digital Flight Control System Development and Flight Testing," Presented at AIAA/SETP/SFTE/SAE/ITEA/IEEE 1st Flight Testing Conference held at Las Vegas, Nevada, on 11-13 November 1981 9AIAA-81-2465).